2.4. Trend analysis (2000-2014) of the snow cover by satellite (MODIS sensor)

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Abstract

The MODIS sensor carried by the satellite Terra of NASA provides information of the snow cover from the year 2000 to the present. The complete time series of the MOD10A2 product has been analysed for Sierra Nevada. This product shows the maximum surface area occupied by snow in 8-day periods. The results display negative trends in the snow cover duration in 79.05% of the pixels of Sierra Nevada. There is also a trend towards a later snow cover onset date in 68.03% of the pixels. In addition, 80.72% tended towards an early snowmelt. These trends are more evident the higher in elevation.

Aims and methodology

The aim of this work is to analyse the changes in the snow cover of Sierra Nevada from 2000 to 2014, using the information provided by the MODIS sensor carried by the satellite Terra of NASA. The snow cover is a landscape element of fundamental importance in Sierra Nevada as its structure and dynamics largely determine the availability of water both in the rivers as well as in the high-mountain ecosystem. It is also responsible for the structure of the vegetation in Alpine environments. The methodology followed is based on the creation of a work flow that automatically processes all the images of the product MOD10A2 (maximum extension of snow for 8 days) of MODIS [15], to generate indicators of the structure of the snow cover (SCD, snow-cover duration, number of days covered by snow per hydrological year; SCOD, snow-cover onset dates, first date in the hydrological year that the pixel has snow; SCMD, snow-cover melting dates, last date in the hydrological year that the pixel has snow) [16]. Below, time-series analysis is applied to characterise the trends of each of the aforementioned indicators in the 7994 pixels comprising Sierra Nevada. The trend analysis evaluates the intensity (adimensional), magnitude (expressed in days early or late), the sign (early or late) and the degree of statistical significance during the analysed period (14 years). Finally, the spatial pattern of these trends was explored according to elevation.

Results

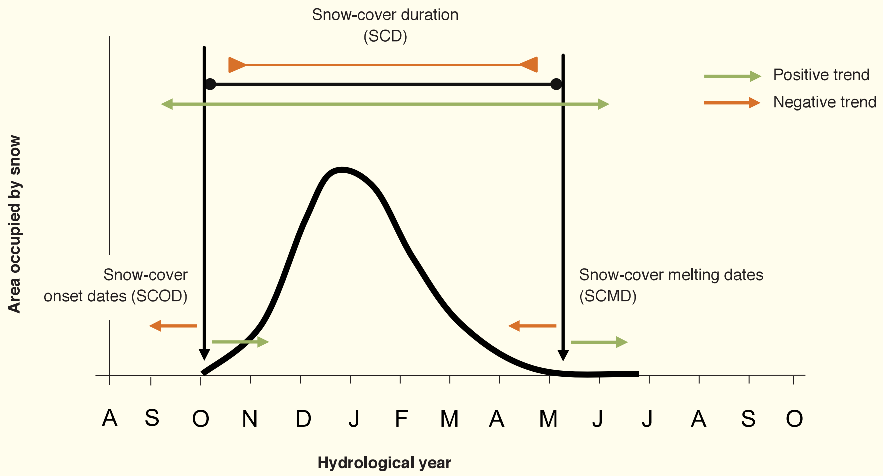
The results show that the snow cover has undergone significant changes in the last 14 years. At the scale of the whole of Sierra Nevada, almost 80% (Table 1) of total pixels showed a negative trend in the duration of the snow cover (see Figure 1 for clarification on the direction of the trends). However, this trend proved significant in only 5.89% of the pixels. The snow-cover onset date showed a similar pattern: 68.03% of the pixels had a positive trend (later starting date). Finally, 80.72% of the pixels followed a negative trend (earlier) for the last date of snow presence.

The values of the trends described above are distributed in the territory following a well-defined spatial pattern. It is clearly visible that both the intensity of the trend (*tau*) and the magnitude (days of change) become more pronounced with elevation. This situation is especially notable in the case of the snow-cover duration (Figure 2). This means that the changes in the structure of the snow cover were most intense in the highest elevations. This spatial pattern is clearly evident in Figure 3, which shows a map with the trends in the duration of the snow cover.

Lastly, the temporal change pattern (on a monthly scale) in the trends of the snow-cover duration on Sierra Nevada were analysed. Although not statistically significant, the results are relevant and consistent with those described above.

Thus, the trends towards a reduction in the duration of snow are more pronounced in the beginning month (October) and the end (May) of the snow period. These results indicate that the snow begins steadily later and the melts earlier in the season. This appears to explain the reduction in the overall duration of the snow described above.

Figure 1



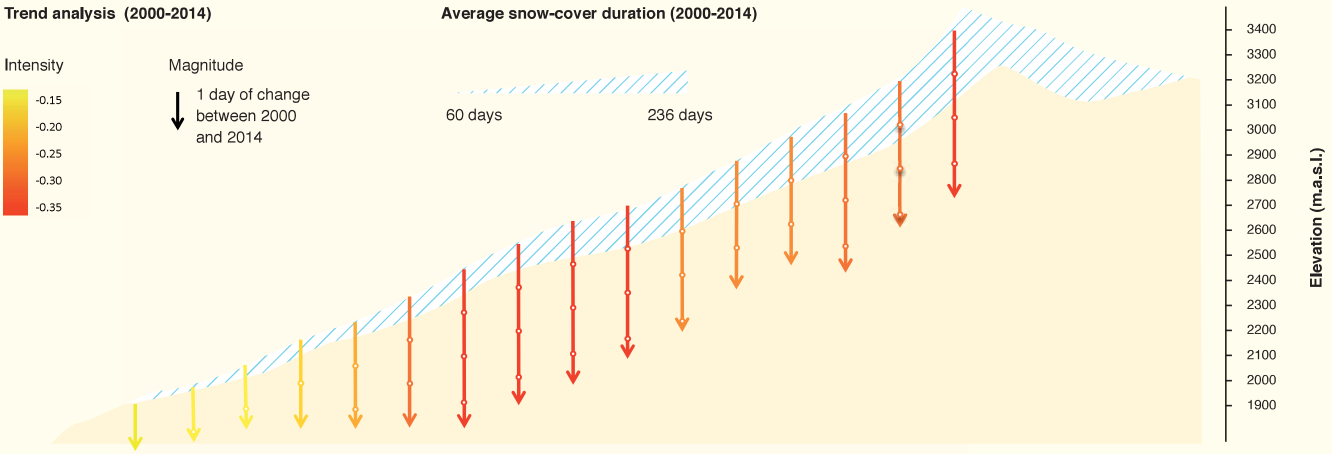
Schematic representing the changes in the surface area occupied by snow over a standard hydrological year. The indicators used to describe the structure of the snow cover are shown. Also, the directions of the trends are indicated. A positive trend in the snow-cover duration implies an increase in this variable. A positive trend in the snow-cover onset date implies a delay in that variable. Positive trends in the snow-cover melting date imply a delay in that variable.

Table 1

		Pixels		Significant pixels	
Variable	**Trend**	***n***	**%**	***n***	**%**
Snow-cover duration (SCD)	Positive Negative	1455 6319	18.2 79.05	6 372	0.41 5.89
Snow-cover onset date (SCOD)	Positive Negative	5438 2380	68.03 29.77	332 59	6.11 2.48
Snow-cover melting date (SCMD)	Positive Negative	1326 6453	16.59 80.72	5 717	0.38 11.11

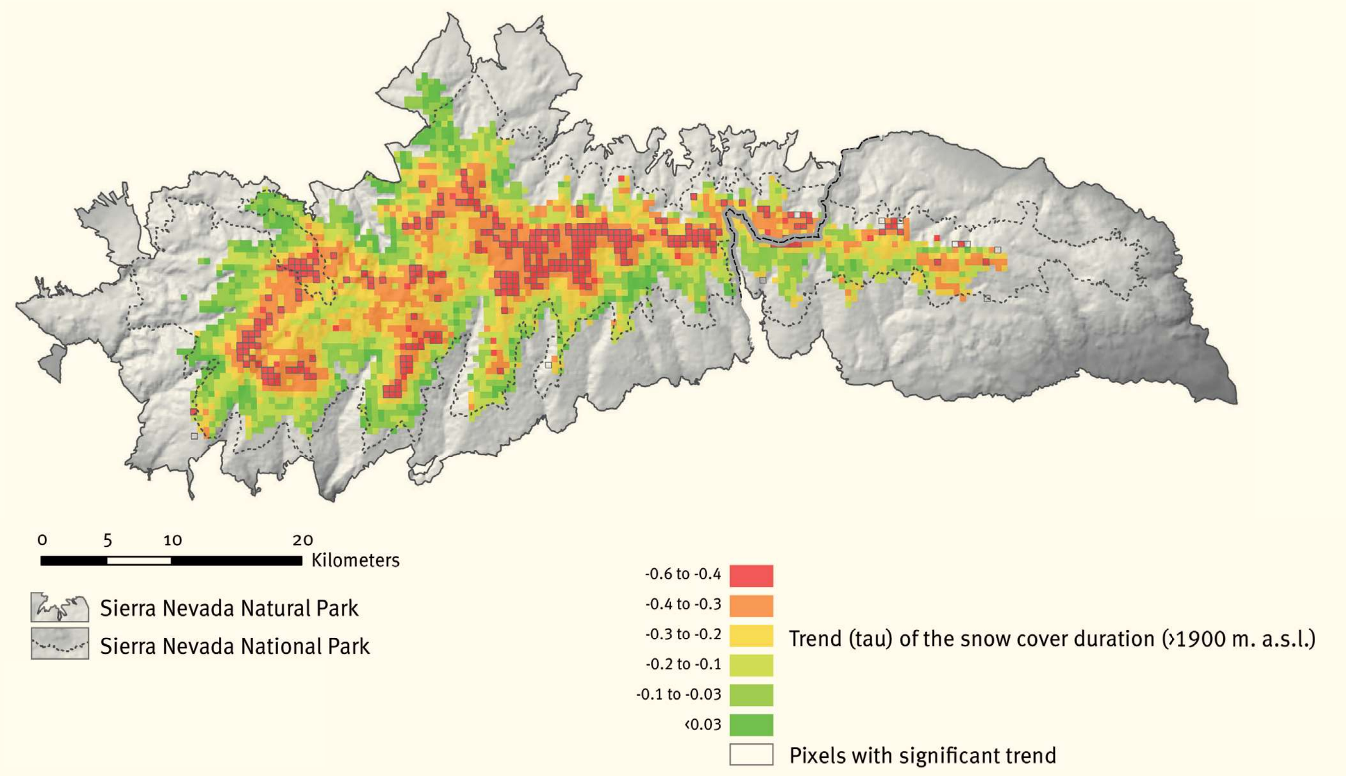
Results of the analysis of the annual trends (Mann-Kendall test) over the last 14 years for the snow-cover duration, the snow-cover onset dates and snow-cover melting dates. For each variable, the number of pixels (n) with negative trends ($\tau < 0$) and positive ones ($\tau > 0$) is shown as well as the number of significant pixels (p-value < 0.05).

Figure 2



Graphic representation of the changes in intensity (*tau*) and in magnitude (slope) of the trend observed for the snow-cover duration in the different elevational ranges (from 1900 to 3500 m.a.s.l.). The colours of the arrows indicate the intensity of the trend in the snow-cover duration (*tau*). The lengths of the arrows located at each elevation indicate the magnitude (expressed in days) of each trend. For instance, in the range of greater elevation, an average magnitude of -3 days was found. This means that the snow-cover duration was reduced in 3 days in the last 14 years.

Figure 3



Map of the trend in snow-cover duration in Sierra Nevada (elevation › 1900 m.a.s.l.). The significant pixels are represented with dark outlines.

Discussion and conclusions

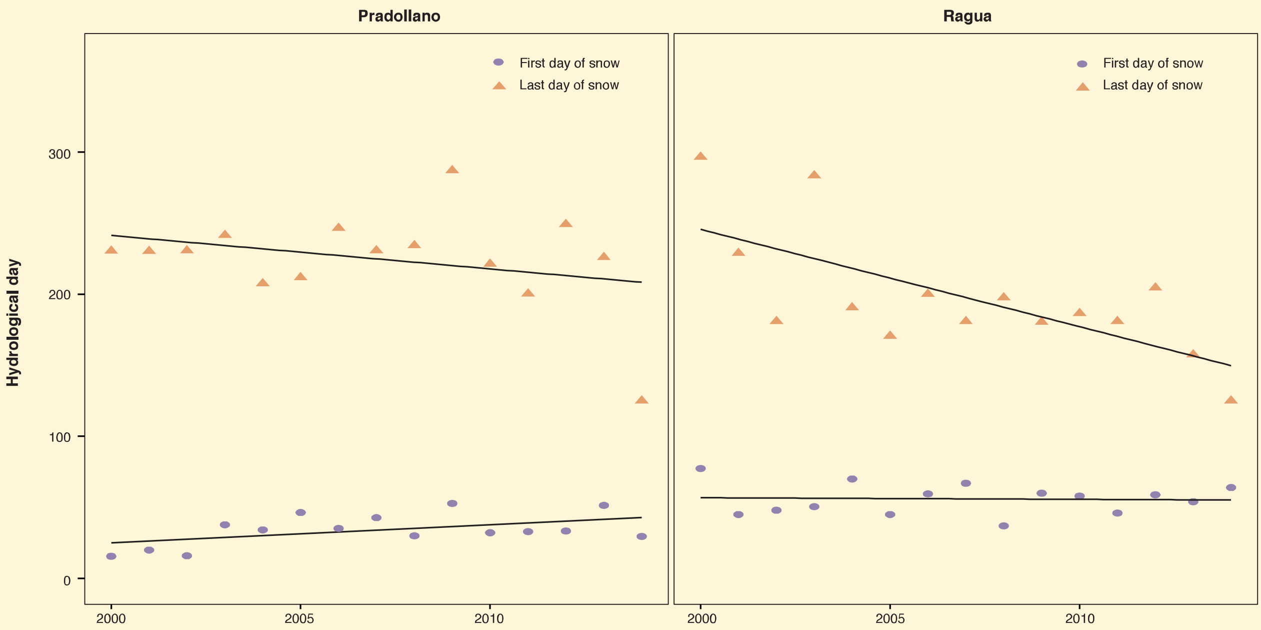
Although the time series considered is not very long (14 years), the trends observed provide preliminary information on the changes that may be occurring in the snow cover of Sierra Nevada. In any case, decreased trend in the snow-cover duration in Sierra Nevada is consistent with that reported in the Alps [17]. However, in other mountains (Central Asia), no such apparent trends have been detected in the same time period as in the present study [18]. This could indicate that the causes of the trends detected are related to local or regional factors, such as the NAO (*North Atlantic Oscillation*) [19].

The trend observed in the snow-cover duration changed over the elevational gradient: the highest areas had more intense trends and greater magnitude towards the reduction of the duration of the snow. This coincides partially with data for precipitation on Sierra Nevada (see Chapter 1) and with other similar studies made in the Alps [17]. The aforementioned gradient of increasing trend intensity with elevation was found also in the annual maximum temperature (see Chapter 1). The link between the the trends of snow-cover duration, the quantity of precipitation, and the annual maximum temperature confirms the causal relationship between climate and snow cover. This relationship is especially important in Mediterranean environments, where a large part of the precipitation falls in spring and winter, and thus the probabilities of precipitation falling in the form of snow are greater.

In short, the time series of the MODIS sensor offers detailed information on the structural and functional behaviour of the snow cover at different spatial and temporal scales. This is of broad interest, given the role of the snow as a provider of ecosystem services.

Trends in the snow cover and ecosystem services

The snow cover constitutes a crucial physical element that determines the structure of the landscape and also the functioning of mountain ecosystems. Furthermore, it serves as a key element for certain economic activities, e.g. snow sports. This reflects the importance of evaluating the potential impact of climate change on the development of this activity. The two figures below describe the trends found in the snow-cover duration, both at the ski resort of Pradollano as well as in that of Puerto de la Ragua. The time course of the first day of snow (circles) and the last day of snow (triangles) are shown for each hydrological year of the series 2000-2014.



Graphs showing the trends on the first and last presence of snow at the ski resort of Pradollano (left) and of Puerto de la Ragua (right), respectively.